

Trade-off between Contrail Reduction and Emissions under Future US Air Traffic Scenarios

Antony D. Evans*

Oak Ridge Associated Universities, Moffett Field, CA, 94035

Neil Y. Chen[†] and Banavar Sridhar[‡]

NASA Ames Research Center, Moffett Field, CA, 94035

Hok K. Ng[§]

University of California, Santa Cruz, Moffett Field, CA 94035

This paper examines how future contrail reduction strategies in the United States, limited by airspace capacity constraints, may impact future CO₂ emissions and average global temperature. Future 2025 air traffic in the National Airspace System is simulated for a series of assumed air traffic growth rates ranging from 1.15 times to 2.0 times 2010 traffic levels. Contrail reduction strategies using altitude changes are then simulated, trading off contrail reduction with increased CO₂ emissions. Altitude changes are limited, however, by airspace sector capacities, according to assumed sector capacity growth scenarios. Future fleet turnover is simulated in order to capture potential changes in CO₂ emissions resulting from the introduction of new technology, based on assumptions about future technology and fleet entry. Sample future sector counts are shown for four sectors with high traffic in Kansas City Air Route Traffic Control Center. The trade-off between system-wide contrail reduction and extra CO₂ emissions, and the resulting impact on absolute global temperature potential is also shown. The results suggest that contrail reduction through altitude changes is likely to have climate benefits under future traffic levels, particularly when aircraft can change altitude by up to 4,000 ft. The results also suggest that, while airspace capacity constraints may reduce the degree to which contrails can be avoided, they are unlikely to significantly reduce the climate benefits of contrail avoidance. These results assume, however, that airspace capacity would increase if the higher forecasts of traffic growth (e.g., 1.5 times or 2 times 2010 traffic levels) materialize. The results also suggest that while different weather days and different assumptions about the climate impact of contrails lead to significant changes in the results, the general trends remain unchanged, and the ratio of contrail reduction to extra CO₂ emissions at which climate impact is minimized remains approximately constant.

I. Introduction

WORLDWIDE demand for air travel has grown significantly over the past five decades. Between 1960 and 2005 worldwide scheduled passenger air travel grew from 109 billion to 3.7 trillion passenger-km travelled – an average growth rate of over 8% per year.^{1,2} Forecasts for future growth are also high – the Intergovernmental Panel on Climate Change (IPCC) forecast a growth rate between 1990 and 2015 of 5% per year¹, which corresponds to that of both the Airbus Global Market Forecast from 2011 to 2030³ and the Boeing Current Market Outlook from 2010 to 2030⁴. By 2050 conservative estimates predict a 30-110% growth in passenger kilometers travelled over 2005 levels⁵, while more aggressive estimates predict an increase of an order of magnitude⁶. Associated with such growth in demand for air travel is a growth in air traffic (number of aircraft movements), which is expected to produce a significant environmental impact, as reported by the IPCC¹ and Cairns *et al.*⁷, including air quality and noise impacts, and global climate change.

* Postdoctoral Fellow, NASA Postdoctoral Program, MS 210-10, Senior Member.

[†] Research Aerospace Engineer, Systems Modeling and Optimization branch, MS 210-10, Member.

[‡] Senior Scientist for Air Transportation Systems, Aviation Systems Division, MS 210-10, Fellow.

[§] Senior Software Engineer, University Affiliated Research Center, MS210-8, Member.

As reported by Waitz *et al.*⁸, the three largest emission impacts on global climate from aviation include direct emissions of greenhouse gases such as carbon dioxide (CO₂), emissions of nitrous oxides (NO_x), and persistent contrails. Strategies have been proposed for mitigating the future environmental impact of these emissions. These include economic strategies such as carbon trading⁹ or cap-and-trade¹⁰ schemes, technological developments such as new engine and airframe technologies, and operational changes such as continuous decent approaches. Approaches have also been suggested for contrail avoidance.^{11,12} Contrails are the clouds that form trails behind aircraft under certain weather conditions, and reduce incoming solar radiation and outgoing thermal radiation in such a way as to accumulate heat.¹³ To reduce the impacts of contrails, operational approaches to avoid contrail formation have been suggested by a number of authors, and typically include altitude change^{14,15,16,17} or lateral path deviation¹⁸ to avoid regions of airspace in which contrails are likely to form. Because existing flight cruise altitudes and flight plans are optimized to minimize fuel burn, maneuvers to avoid contrail formation typically result in increased fuel burn and CO₂ emissions. A trade-off therefore exists between contrail reduction and increased CO₂ emissions. This is examined in detail by Ref. 19, which identifies strategies to avoid contrails based on a user-defined trade-off factor to trade off between contrail reduction and extra emissions. The impact of this trade-off on global average temperature is examined in detail by Ref. 20 for a subset of flights operating between 12 city pairs.

These previous studies do not examine if there is likely to be an increase in airspace congestion in the future resulting from changes in either altitude or lateral flight path to avoid the regions of contrail formation. While Ref. 19 finds that increases in airspace congestion due to contrail avoidance in the US National Airspace System (NAS) would not lead to an increase in sector counts above capacity in the current system (2010), this may not be the case in the future. Therefore, given future air traffic and future airspace capacity constraints, it is unclear to what extent contrail avoidance will be practical, and to what extent it will be possible to limit the negative climate impacts of increased contrail formation.

This paper examines how future contrail reduction strategies in the United States, limited by airspace capacity constraints, may impact future CO₂ emissions and average global temperature. Future air traffic in the NAS is simulated for a series of assumed air traffic growth rates. We then simulate contrail reduction strategies, limited by airspace sector capacity constraints, which are defined according to assumed sector capacity growth scenarios. Absolute global temperature potential (a metric for measuring global average temperature change) is then simulated based on assumptions about the impact of the resulting CO₂ emissions and contrails on the global climate. The contrail reduction strategies simulated are consistent with Ref. 19, including only altitude change, but trading-off contrail reduction with increased CO₂ emissions. The assumptions about the impact of CO₂ emissions and contrails on the global climate are consistent with Ref. 20. The modeling approach is described in detail in Section II, and results are presented in Section III. This is followed by a sensitivity analysis in Section IV and conclusions in Section V.

II. Approach

A. Future Air Traffic

Forecasts of air traffic growth within the United States vary significantly. In 2004, NextGen, the future US air transportation system, was forecast to provide airspace capacity to accommodate up to three times 2004 traffic by 2025.²¹ Assuming a constant growth rate, this forecast of 2025 traffic amounts to 2.2× the 2010 traffic forecast at the time. The forecast was based on assumptions about a potentially significant increase in the use of micro-jet aircraft and air-taxi services. Such growth has not materialized, and combined with the effects of the downturn in the economy, more recent forecasts are lower. The 2011 FAA Aerospace Forecast²² predicts NAS air traffic in 2025 of 1.25× 2010 traffic, while the FAA Terminal Area Forecast for 2009²³ predicts it to be 1.3× the 2010 traffic forecast at the time. Ref. 24, which applies airport and airspace capacity constraints to the Terminal Area Forecast, reduces the forecast of 2025 traffic even further, to as low as 1.04× 2010 traffic. In contrast to these reduced traffic forecasts for 2025, Ref. 25 (based on a 2005 base year) predicts growth of 1.5× the 2010 traffic forecast in the same paper, while Ref. 26 predicts growth in 2025 of between 1.3× and 1.8× 2010 traffic. These forecasts differ from the FAA forecasts in that they are based on passenger demand forecasts, which account for changes in expected GDP per capita, city populations and income per capita. The FAA forecasts are based primarily on historical trends in airport traffic, as well as a number of other airport specific considerations.

Because of these large variations in NAS air traffic forecasts, a number of different growth rates are simulated in this paper to represent 2025 traffic. These are as follows: 1.15×, 1.2×, 1.5× and 2.0× 2010 traffic. The 2010 traffic is scaled using the *AvDemand* tool developed by Sensis Corporation.²⁷ A single day of historical track data was input to the tool, which scaled it directly according to the specified rate to represent a day of traffic in 2025. The aircraft track data used was for September 24, 2010, provided by the FAA's Aircraft Situation Display to Industry (ASDI).

Homogenous traffic growth was applied across all airports. New flights were distributed between the departure times of the first and last flights in the original schedule based on the departure distribution of the original schedule. This means that, if the original flight schedule distribution was heavy in the early morning, light during the daytime and again heavy in the early evening, the newly created flights on the flight segment are distributed based on the same schedule pattern as the original schedule. Although *AvDemand* also has the capability of adjusting flight schedules in such a way that airport schedules do not exceed specified airport capacities at any time during the day, this was not applied in this paper, resulting instead in traffic that was scaled exactly relative to the input file.

In the generation of the initial *AvDemand* forecasts, fleet mix is assumed to remain identical to that of the input track data from September 24, 2010. However, because we simulate a trade-off between contrail reduction and increased CO₂ emissions, it is important to simulate future changes in fleet fuel efficiency. With increased fleet fuel efficiency, additional CO₂ emissions from contrail avoidance maneuvers are reduced, increasing the environmental benefit of lowering contrails, and decreasing the cost associated with doing so. This may, however, increase airspace congestion above what it would be were fleet fuel efficiency not to improve, because more contrail avoidance maneuvers would be possible for a given amount of extra fuel burn.

Predictions for the fuel burn improvements associated with new technology can vary significantly, because new technology development and deployment times rely on several external factors, such as fuel price, equipment cost, the financial state of the airlines, etc., which are all challenging to predict. Ref. 24 presents fleet entry and fuel burn improvement rates for a series of technology forecasts. These forecasts are extracted from NASA and FAA technology projections²⁸, a market-based forecast, developed by the Joint Project Development Office's (JPDO) Environmental Working Group (EWG) Technology Standing Committee (TSC)²⁹, and an intermediate technology projection using the Environmental Design Space (EDS)^{30,31}. In this paper, we apply the EDS projection, which is presented in Table 1, interpolating linearly to calculate 2025 schedule insertion levels. The projection includes two stages of aircraft technology development (+1 and +2 in the table) beyond existing (standard) technology, which are described in greater detail in Ref. 30 and 31.

Table 1. Future fleet composition including new aircraft technology, based on the EDS technology projection.

Technology Level	Relative Fuel Efficiency	Fleet Composition				
		2010	2020	2030	2040	2050
Standard	1.0	100%	92%	63%	46%	41%
RJ+1	0.9	-	4%	5%	3%	-
SA+1	0.86	-	3%	12%	2%	-
STA+1	0.81	-	1%	1%	1%	-
LTA+1	0.81	-	0%	1%	0%	-
RJ+2	0.75	-	-	3%	14%	20%
SA+2	0.75	-	-	14%	31%	34%
STA+2	0.87	-	-	1%	3%	5%
LTA+2	0.82	-	-	0%	0%	0%

The fuel burn rates in Table 1 are specified relative to reference aircraft for each of the specified size categories listed. These reference aircraft are as follows:

- Regional jet (RJ): Canadair RJ-900, operating CF34-8C1 engines
- Small single aisle (SSA): Boeing 737-700, operating CFM56-3C-1 engines
- Large single aisle (LSA): Boeing 737-800, operating CFM56-3C-1 engines
- Small twin aisle (STA): Boeing 777-200, operating GE90-110B1 engines
- Large twin aisle (LTA): Boeing 747-400, operating CF6-80C2A5 engines

Note that while the single aisle size category has both small and large reference aircraft (SSA and LSA), schedule insertion levels are specified for both, together, in Table 1, listed as SA. All flights in the output from *AvDemand* are allocated to an aircraft size category (RJ, SSA, LSA, STA or LTA), based on the size of their originally specified aircraft types. A fixed number of these flights, defined by the schedule insertion levels specified

in Table 1, are then “upgraded” to new types based on the reference aircraft by size category, and the relative fuel efficiency from Table 1. These new types, along with old types that were not upgraded are then used in the simulation of contrail avoidance, and the trade-off with CO₂ emissions. This is described below.

B. Contrail Modeling and Contrail Avoidance Strategy

Contrails form when ambient Relative Humidity with respect to Water (RH_w) is greater than a critical value, r_{contr} ,³² which varies with air temperature. Contrails persist when the environmental Relative Humidity with respect to Ice (RH_i) is greater than 100%³³. When RH_w exceeds 100%, clouds are present³⁴. Thus, in this paper, we assume that contrails are likely to form in regions of airspace where $r_{contr} \leq RH_w < 100\%$ and $RH_i \geq 100\%$. These regions of airspace are identified for a sample day with high incidence of contrails, April 23, 2010, by calculating r_{contr} , RH_w , and RH_i as described by Ref. 19, based on air temperature and pressure from Rapid Updated Cycle (RUC) data, provided by the National Oceanic and Atmospheric Administration (NOAA). Contrails only have a negative environmental impact during the night. However, in this paper we do not model the duration of persistent contrails. We instead assume that all persistent contrails remain long enough to have a negative impact during the following night.

Contrails are quantified using a Contrail Frequency Index (CFI), defined in Ref. 19 as the total number of flight minutes spent in a region of airspace in which contrails are likely to occur. The regions of airspace are defined based on 13 km RUC data, equivalent to volumetric units of 13km × 13km square × 1 flight level (2,000ft) deep. RUC data for each volumetric unit across the United States between 26,000ft and 44,000ft (the altitudes at which aircraft typically fly and at which contrails occur) is analyzed to determine whether contrails are likely to occur for the sample weather day. Flight track data are then used to determine the duration of flight tracks through each volumetric unit. In regions of airspace in which contrails are likely to occur, CFI is also calculated for tracks one and two flight levels (2,000ft and 4,000ft respectively) above and below the original track altitude, if feasible, in order to simulate potential altitude change for contrail avoidance. Altitude changes are considered infeasible if the ceiling of the aircraft type in the track data is exceeded by the altitude change, or if the aircraft’s altitude change violates a sector capacity constraint. In such a case, an aircraft would be forced to make a different maneuver (change to a different altitude not within the constrained sector), or not to maneuver at all.

C. Fuel Burn and Emissions Modeling

In order to study the trade off between contrail formation and CO₂ emissions, fuel burn (which is directly proportional to CO₂ emissions) is estimated for all aircraft flying through regions of airspace in which contrails are likely to form, at each of the flight levels considered for contrail reduction. Fuel consumption is modeled using the Eurocontrol Base of Aircraft Data (BADA) Revision 3.7³⁵. BADA takes inputs from the flight track data, including aircraft type, weight, altitude and speed, allowing kilograms of fuel and CO₂ emissions to be estimated.

The trade off between contrail formation and CO₂ emissions is defined by a parameter, α , which relates the impact of a change in contrails to a change in CO₂ emissions, as described by Ref. 19. It is a user-defined trade off factor that can be interpreted as the equivalent CO₂ emission in kg that has the same impact as 1 minute of contrail (a CFI of 1). Given α , a contrail reduction strategy would shift aircraft from flight level l to flight level l' if the following equation is satisfied:

$$\Delta C_{l,t}^{l'} > \frac{1}{\alpha} \Delta E_{l,t}^{l'} \quad (1)$$

where:

$$\Delta C_{l,t}^{l'} = C_{l,t}^{l'} - C_{l,t}^l \quad (2)$$

$$\Delta E_{l,t}^{l'} = E_{l,t}^{l'} - E_{l,t}^l \quad (3)$$

$C_{l,t}^l$ and $E_{l,t}^l$ are the CFI and total CO₂ emissions, respectively, before any change in altitude, while $C_{l,t}^{l'}$ and $E_{l,t}^{l'}$ are the CFI and total CO₂ emissions, respectively, after guiding aircraft from the initial flight level l to the new flight level l' . For maximum contrail reduction, $\alpha = \infty$, in which case the effect of emissions are ignored. When $\Delta E_{l,t}^{l'}$ is positive (i.e., a change in cruise altitude increases the aircraft fuel burn, which is almost always the case as aircraft typically cruise at their fuel optimal altitude), $\alpha = 0$ corresponds to no contrail reduction strategy, since equation (1) can never be true.

Identifying the appropriate value for α requires consideration of all the different impacts of contrails and extra CO₂ emissions, and will vary by stakeholder. For environmental considerations, α should be selected by accounting for the relative climate impact of both contrails and CO₂ emissions, as described in Subsection D, below. However, other impacts, such as increased fuel use, and therefore increased operating costs, as well as costs associated with

any increase in airspace congestion, may also be considered important by some stakeholders. Two approaches to identifying α are described by Ref. 19: monetization of the value of both contrails and emissions, as suggested by Ref. 36 (most applicable to minimizing cost); and considering contrails and emissions as disturbances to the global climate equilibrium, and measuring the impact as changes to the global mean surface temperature, as suggested by Ref. 37 (most applicable to minimizing climate impact). While we estimate the impact of CO₂ emissions and contrails on global mean surface temperature in this paper, as in Ref. 37, we do not attempt to identify a desired value for α , as this is seen as a policy question outside the scope of this paper. We do, however, inform policy makers by identifying the values of α that would minimize climate impact.

Using the estimated CFI and CO₂ emissions calculated for each possible altitude change, we identify a strategy for trading off contrail reduction and increased emissions by identifying the altitude changes that satisfy equation (1), given α . These strategies are identified for a range of α values in order to study the sensitivity of the results to α .

D. Climate Change Metric: Pulse Absolute Global Temperature Potential

In this paper we model the impact of changes in CO₂ emissions and contrails on the global climate using a series of linear dynamic systems, as described in Ref. 20. These linear systems are generated against a background of concentrations of various greenhouse gases resulting from past emissions from all sources (both natural and anthropogenic). They output the changes to these greenhouse gas concentrations resulting from emissions from the modeled aircraft operations, which are assumed to be small in comparison to the background concentrations. A third order linear system is used to describe the CO₂ concentration dynamics, while the concentration dynamics of other greenhouse gases are described by first order linear systems. The radiative forcing associated with each gas is approximated by simple functions of these concentrations^{20,38}. The temperature response of the global climate to this radiative forcing, and the radiative forcing associated with contrails, is quantified using a climate metric, Absolute Global Temperature Potential (AGTP). This metric adapts a linear system for modeling the global temperature response to aviation emissions and contrails. AGTP was chosen because it accounts for the very different characteristics of aviation emissions and contrails, particularly with regard to the lifetime associated with each, which differ significantly (contrails have a lifetime in the order of hours, while CO₂ has a lifetime in the order of a hundred years). AGTP is calculated for CO₂ emissions and contrails as described in Ref. 20. In this paper we calculate the pulse AGTP, which measures the change in global temperature at a particular time t in the future, due to an instantaneous disruption at t_0 .

Parameter values used to calculate pulse AGTP for CO₂ emissions and contrails include the specific forcing due to CO₂ taken as $1.82 \times 10^{-15} \text{ Wm}^{-2}\text{kg}^{-1}$, from Ref. 39. The results in Section III-C apply a time horizon H of 50 years, although three values for H are considered in the sensitivity analysis in Section IV-B: 25 years, 50 years, and 100 years. Net radiative forcing for contrails, including both long wave and short wave radiative forcing, is assumed to be 10 Wm^{-2} , according to Ref. 40. In calculating the amount of energy induced to the atmosphere for a unit length of contrail over its lifetime, we assume the contrail width to be 1,000m and the lifetime to be 10,000s. An efficacy factor, defined as the ratio of global temperature increase for a local energy input relative to that for a CO₂-equivalent globally distributed energy input, is used to differentiate the way radiative forcing from CO₂ and contrails affect the climate. In Section III-C we apply an efficacy of 0.8, but in the sensitivity analysis in Section IV-B it is assumed to vary from 0.6 (the value for annual mean contrail cover estimated by Ref. 41) to 1.0.

E. Airspace Capacity Growth

The impact of airspace capacity constraints on future contrail avoidance is analyzed by comparing 15-minute sector counts to the sector Monitor Alert Parameter (MAP) values, representing airspace capacity. In the existing system, airspace capacity is restricted by assigned MAP values, which represent the maximum number of aircraft that can simultaneously occupy a sector within a 15-minute time window. Sector counts are made using sector coordinates and flight track data.

In the future, airspace capacity is likely to increase. Under NextGen, concepts and technology are being developed to specifically increase throughput in the NAS, and to achieve higher efficiency in utilizing NAS resources such as airports, en route airspace, and terminal airspace⁴². Ref. 24 describes current research in a number of key research focus areas which are likely to impact airspace capacity in the future, including Dynamic Airspace Configuration (DAC) and Separation Assurance (SA). DAC is a new operational paradigm that seeks to modify static airspace resources by temporally increasing capacity based on the movement of resources.⁴³ SA aims to identify trajectory-based technologies and human/machine operating concepts that would safely support a substantial increase in capacity, such as the Automated Airspace Concept (AAC)⁴⁴ that generates conflict resolution trajectories that it then sends to the aircraft via a data link.

MAP values are the current FAA measure of sector capacity. For the results presented in Section III, we vary the

simulated MAP values based on the level of future traffic simulated. For $1.15\times$ and $1.2\times$ traffic, we assume that MAP values remain unchanged from their existing values, since $1.15\times$ and $1.2\times$ traffic do not typically violate these capacity constraints. However, for $1.5\times$ and $2.0\times$ traffic, the existing MAP values would be routinely violated, even with no contrail avoidance. We therefore assume that, through NextGen developments, the MAP values for all sectors will increase in 2025, by 66% and 75% respectively under $1.5\times$ and $2.0\times$ traffic, which are the increased sector capacities simulated in Ref. 24.

Sample sector counts are presented for four sectors in Kansas City Air Route Traffic Control Center (ARTCC) (ZKC) to illustrate the impact of future contrail avoidance on airspace congestion. These are Sectors 28, 29, 30 and 31. Sector 31 has the highest sector count at 8am EDT on April 23, 2010 (the weather day simulated in Section III), while sectors 28, 29 and 30 are the *high* altitude sectors below sector 31 (a *superhigh* altitude sector). These sectors are illustrated in Figure 1. The boundary between the sectors is at 37,000ft, so any increase in cruise altitude in this region of airspace that causes a flight to move from below this altitude to above it, would lead to a decrease in the sector counts in sectors 28, 29 and 30, and an increase in the sector count in sector 31. Similarly a decrease in cruise altitude in this region of airspace that causes a flight to move from above 37,000ft to below it, would lead to a decrease in the sector count in sector 31, and an increase in the sector counts in sectors 28, 29, and 30. We do not allow flights to shift flight level if, by doing so, the sector capacity would be violated. Flights are therefore allowed to shift flight level until the sector count reaches the sector capacity, at which point no more flights are permitted to shift to that sector. They are, however, permitted to shift to other flight levels, if, by doing so, no sector capacity is violated. In cases where the baseline sector count, with no contrail avoidance, violates the applied sector capacity, this traffic is not moved. Instead, it is assumed that, for this period, the increased sector count is allowable. This typically occurs infrequently, and for only very short periods.

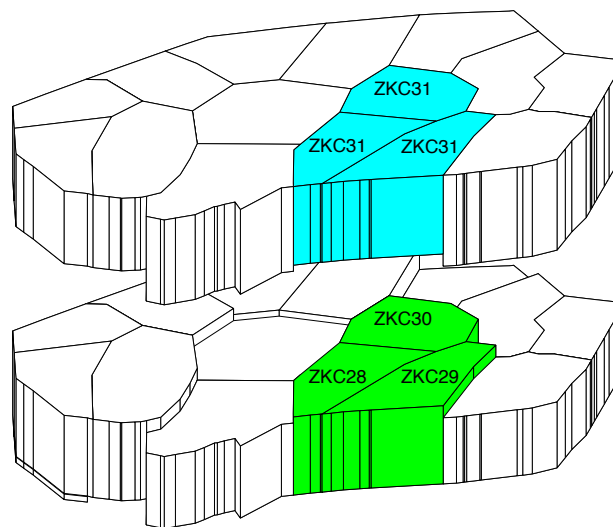


Figure 1. Kansas City ARTCC sector 28, 29, 30 and 31.

III. Results

The results for the analysis described above, given the incidence of contrails on April 23, 2010, are presented in the following section, and include:

- Sector counts for ZKC28, ZKC29, ZKC30 and ZKC31 at 2010 traffic levels, and at a range of forecast 2025 traffic levels, with and without contrail reduction strategies.
- The trade-off between contrail reduction and extra CO₂ emissions at 2010 traffic levels, and at a range of forecast 2025 traffic levels.
- The trade-off between change in AGTP and extra CO₂ emissions at 2010 traffic levels, and at a range of forecast 2025 traffic levels.

A. Sector Counts

Figure 2 shows sector counts for ZKC28 and ZKC31, at 2010 traffic levels. Sector counts were also plotted for ZKC29 and ZKC30 but are similar to that of ZKC28 so are not presented here. The results in Figure 2 are only

plotted from 12h00 to 21h00 EDT because this is the period of the day when the count is highest in these sectors. The sector count before any contrail avoidance strategies are applied is shown, along with sector counts under contrail avoidance strategies in which aircraft can be shifted by one and two flight levels (2,000ft and 4,000ft respectively). In both cases, maximum contrail avoidance strategies are applied ($\alpha = \infty$). Also shown are existing MAP values for each sector, providing an indication of how close to the sector capacity the sector count is. The traffic is generally busiest in ZKC31, but before any contrail avoidance strategies are implemented, none of the sectors reach capacity at any time, although there are moments when the sector count is close to the MAP value (e.g., ZKC28 at 17h45 and ZKC31 at 17h40).

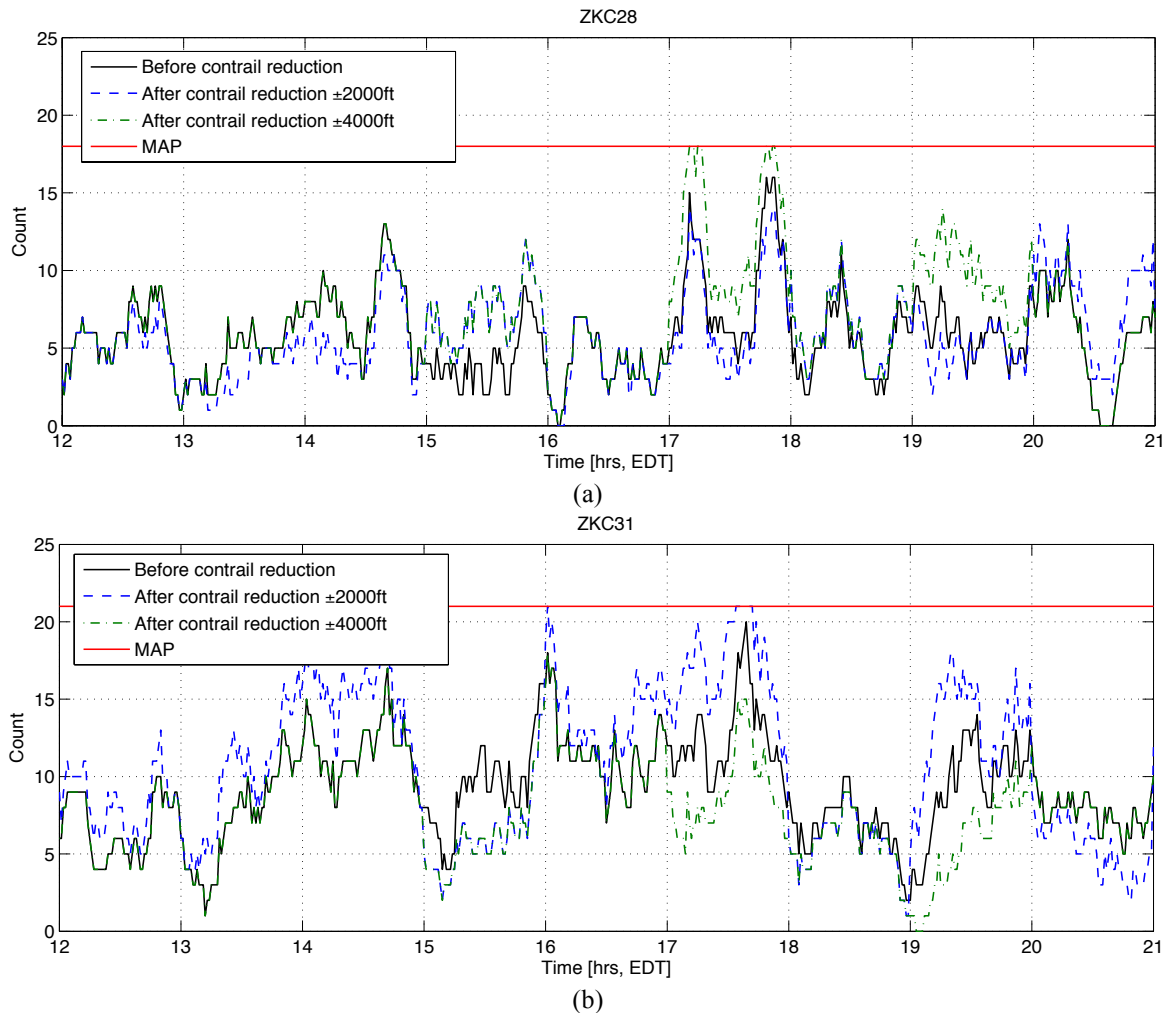


Figure 2. Comparison of 2010 sector counts before and after maximum contrail avoidance: a) ZKC28, and b) ZKC31.

Allowing a shift in aircraft by only one flight level (2,000ft), there is a small decrease in the sector counts in ZKC28, ZKC29 and ZKC30 over most time periods, and a corresponding increase in the sector count in ZKC31. Given that ZKC31 is the *superhigh* altitude sector above the *high* altitude sectors ZKC28, ZKC29 and ZKC30, this indicates an increase in aircraft flight altitude for contrail avoidance (from FL360 to FL380).

It should be noted that this result is specific to the weather scenario simulated, and could be quite different for another weather scenario. For example, if the weather scenario was such that the greatest reduction in CFI could be achieved by descending from FL380 to FL360, ZKC31 would see a drop in sector count, while the *high* altitude sectors would see an increase (such as between 15h00 and 16h00 EDT). For this reason, other weather days were also simulated, the results for which are shown in Section IV-A. The result in Figure 2 illustrates that contrail avoidance can lead to significant changes in sector counts. Even at this 2010 traffic level, the sector counts in ZKC31 reach the MAP value in a couple of cases, indicating that contrail avoidance can lead to increased airspace

congestion. These instances are short (less than 10 minutes), indicating that at existing traffic levels sector capacity is unlikely to be a significant constraint (very few flight altitude changes are prevented by the sector constraint).

When flights are allowed to shift up to two flight levels (4,000ft), traffic moves from the *superhigh* altitude sector to the *high* altitude sectors between 15h00 and 16h00 EDT and after 17h00 EDT. The opposite phenomenon occurs when flights are allowed to shift by only one flight level. This is because, in this weather scenario, a drop in cruise altitude from FL380 to FL340 (two flight level change) yields a greater reduction in CFI than a climb from FL360 or FL380 (one flight level change). Again, this is specific to the weather scenario simulated, but indicates the difference in results possible under different scenarios.

Similar to Figure 2, Figure 3 shows sector counts for ZKC28 and ZKC31 under the highest 2025 forecast traffic levels ($2.0\times$ 2010 traffic levels) with maximum contrail avoidance strategies applied ($\alpha = \infty$). Again, sector counts were also made for ZKC29 and ZKC30, but are similar to that of ZKC28. The original MAP values along with the modified MAP used for the sector count constraints reflecting the 75% sector capacity increase are also displayed in Figure 3. Even with no contrail avoidance strategies in place, existing MAP values are exceeded in a number of instances, illustrating the need for increased capacity if this traffic forecast were to materialize. In ZKC28 the sector counts with no contrail avoidance are well below the potential future capacity scenarios ($1.75\times$ MAP), but in sector ZKC31, the *superhigh* altitude sector, the traffic exceeds even the $1.75\times$ MAP value in two instances (16h00 and 17h40), but only for short periods, which is considered acceptable.

Allowing a shift in traffic by only one flight level (2,000ft), there is a small decrease in the sector count in ZKC28, shown in Figure 3a, over most time periods. There is a corresponding increase in the sector count in ZKC31, shown in Figure 3b, similar to the results shown in Figure 2 and for the same reason. The decrease in sector count in the *high* altitude sectors reduces the traffic, having a positive impact on airspace congestion. However, there is an increase in sector count in the *superhigh* altitude sector (ZKC31) through much of the day. If no sector constraint were applied, this increase in traffic would be significantly greater, reaching as high as $2.7\times$ the existing MAP value at times. In Figure 3b, however, the sector constraint of $1.75\times$ MAP is applied. These results suggest, however, that, under high forecast traffic growth, contrail avoidance strategies may lead to airspace congestion issues in some sectors, and under some weather days, making increases in airspace capacity through NextGen essential.

With a shift in traffic by up to two flight levels (4,000ft), there is an increase in sector count in ZKC28 between 15h00 and 16h00 EDT and after 17h00 EDT, and a corresponding decrease in sector count in ZKC31. Again, this is similar to Figure 2 and for the same reason. Between 16h00 and 17h00 EDT the traffic shifts in the opposite direction, from ZKC28 to ZKC31, with the greatest contrail reduction achieved by shifting traffic from FL360 to FL380. The changes in sector count in this scenario are also high, with ZKC28 even reaching the increased capacity MAP in one case. ZKC31 is not at capacity for as long as in the case where traffic is shifted by one flight level, although this is specific to this weather day and may not be the case on other days.

The results presented in Figure 3 suggest that, under high traffic forecasts for 2025, airspace capacity may be a constraint, particularly with contrail avoidance procedures in place that potentially shift traffic from one sector to another. If this high traffic forecast were to materialize, there would be a need for increases in airspace capacity, as modeled.

Figure 4 shows sector counts for sectors ZKC28 and ZKC31 under the lowest 2025 forecast traffic level ($1.15\times$ 2010 traffic levels) with maximum contrail avoidance strategies applied ($\alpha = \infty$). Again, sector counts were also computed for ZKC29 and ZKC30, but are similar to that of ZKC28. The same sector counts are plotted as in Figure 2 and Figure 3, along with existing MAP values for each sector. The results are generally similar to those in Figure 2 for 2010. Before any contrail avoidance strategies are implemented the sector count only exceeds capacity once, at 17h40 in ZKC31.

Allowing a shift in traffic by only one flight level (2,000ft), there is a small decrease in the sector counts in ZKC28, like in the 2010 case, and an increase in the sector count in ZKC31, up to the sector capacity in a number of instances. With a shift in traffic by up to two flight levels (4,000ft), there is an increase in sector count in ZKC28 between 15h00 and 16h00 EDT, and after 17h00 EDT, up to the sector capacity in two instances, and a corresponding decrease in sector count in ZKC31, similar to the results in Figure 2. While the shifts in flight level in this scenario are also impacted by the sector capacity constraints, only the existing MAP value is applied, and it does not limit contrail avoidance in many instances. Again it is noted that this result is specific to the weather scenario simulated, and may be significantly different for other weather days.

The results presented in Figure 4 suggest that, under low traffic forecasts for 2025, airspace capacity is less likely to be a constraint, although contrail avoidance procedures may still lead to congestion at times. If this low traffic forecast were to materialize, there would be less need for increases in airspace capacity, as modeled.

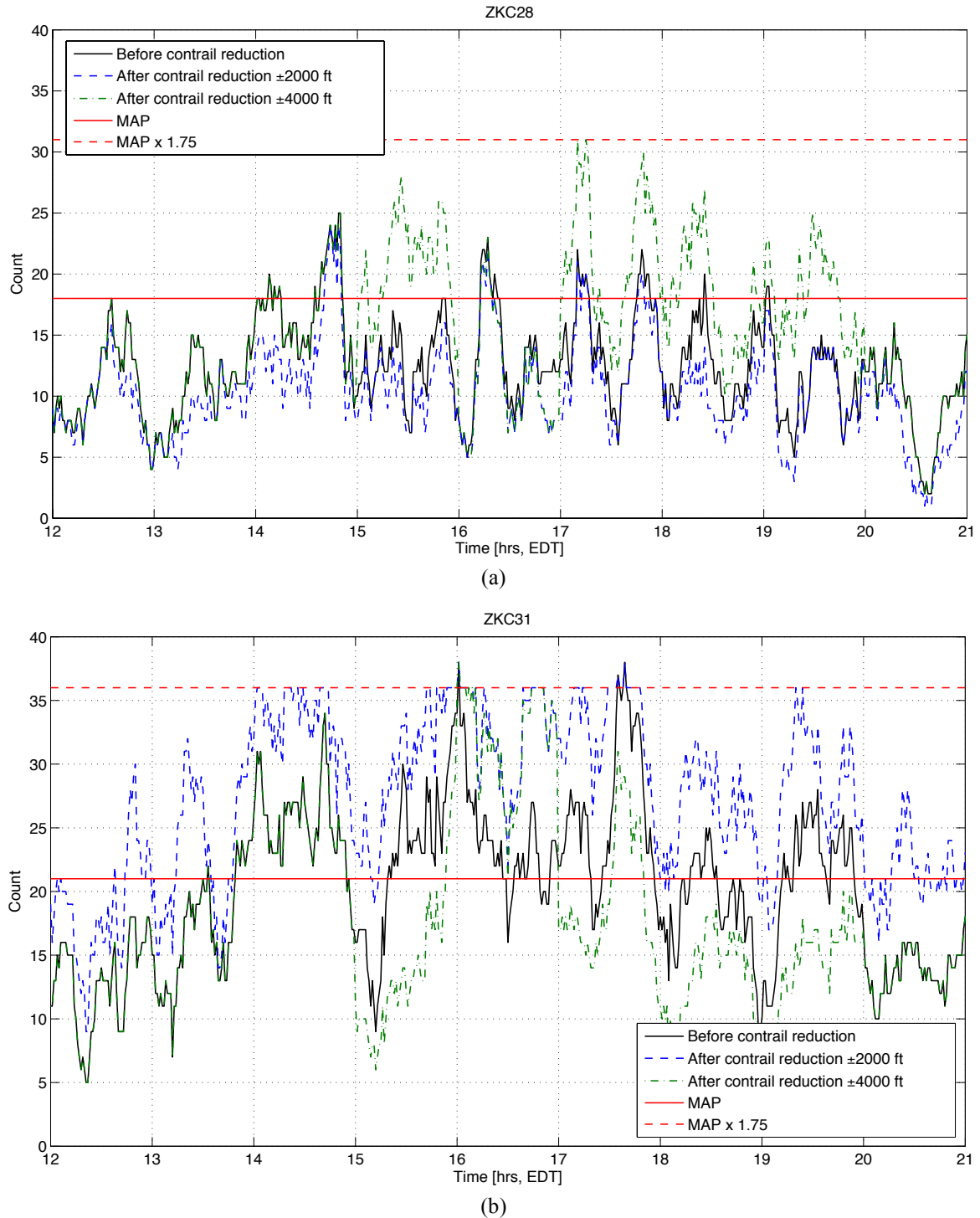


Figure 3. Comparison of 2025 sector counts before and after maximum contrail avoidance, high traffic forecast (2.0x 2010 traffic), with sector constraint (1.75xMAP) applied: a) ZKC28, and b) ZKC31.

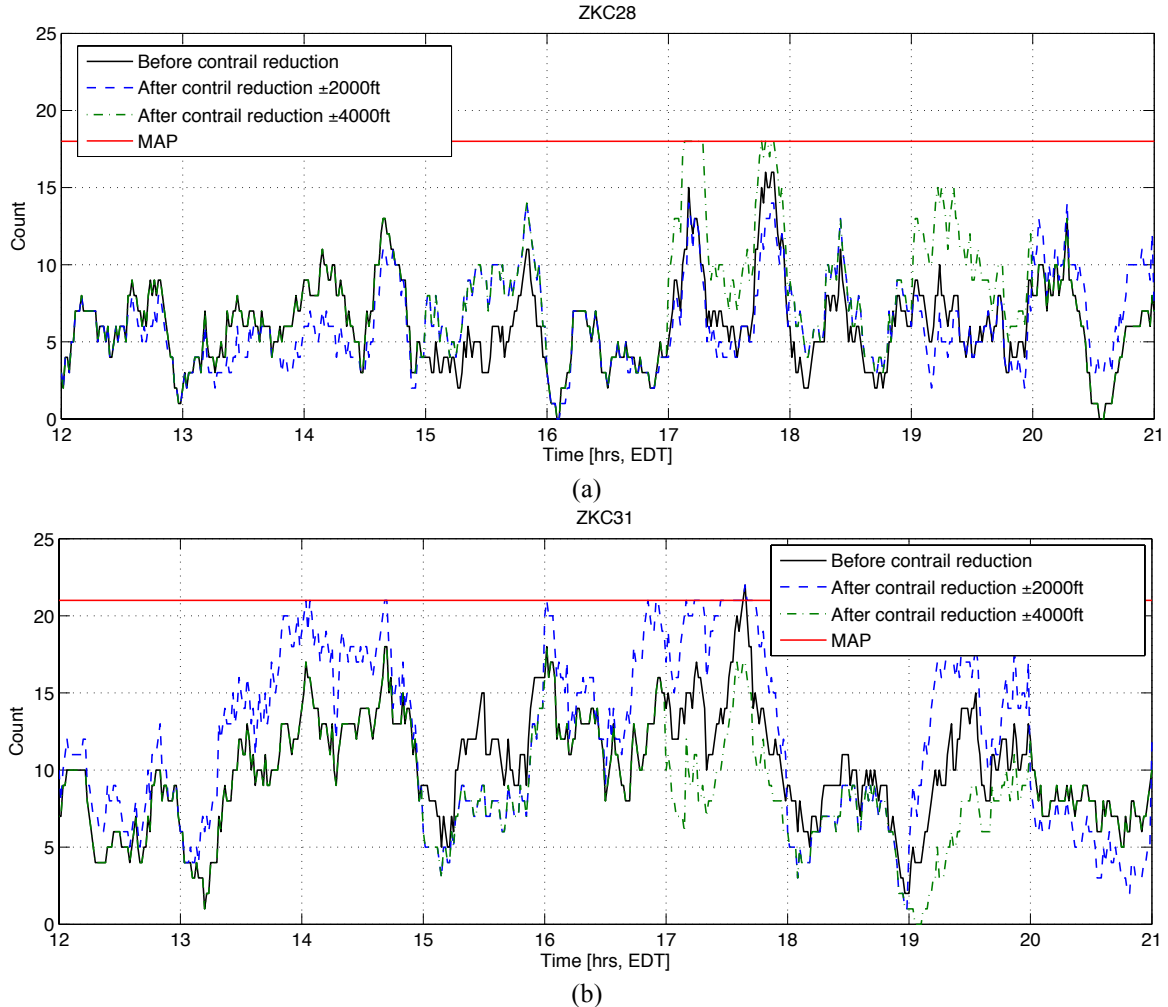


Figure 4. Comparison of 2025 sector counts before and after maximum contrail avoidance, low traffic forecast ($1.15\times$ 2010 traffic), with sector constraint (MAP) applied: a) ZKC28, and b) ZKC31.

B. Trade-off between Contrails and Emissions

Figure 5 shows the trade-off between CFI reduction and extra CO_2 emissions under different values of α . This trade-off is plotted for 2010 traffic levels, and for a range of 2025 forecast traffic levels ($1.15\times$, $1.2\times$, $1.5\times$ and $2.0\times$). Results are plotted for α values of 0, 20, 40, 80 and ∞ , from left to right. Figure 5a shows results allowing a shift in traffic by one flight level ($2,000\text{ft}$) up or down, while Figure 5b shows results allowing a shift in aircraft by up to two flight levels ($4,000\text{ft}$) up or down. In all cases, under low values of α (point to the lower left of each curve), the reduction in CFI is large relative to the extra CO_2 emissions. As α increases (moving towards the upper right of each curve), the reduction in CFI increases at a slower rate than extra CO_2 emissions. As the traffic forecast increases, however, there is a general shift to larger reductions in CFI, with smaller increases in the extra CO_2 emissions. The reason for this is the simulated fleet turnover and entry of new technology into the fleet, which reduces the fleet fuel burn rate, and therefore fleet CO_2 emission rate. The same fleet turnover rates and entry of new technology is simulated in each 2025 traffic forecast. In the $1.15\times$ result, the improvement in fleet fuel burn is sufficient to almost completely offset the increase in CO_2 emissions due to the increased traffic. In fact, at high values of α , there is a slight decrease in CO_2 emissions from 2010 to 2025. For lower values of α there is only a slight increase in CO_2 emissions between the 2010 result and the $1.15\times$ 2025 traffic result. In the $1.2\times$, $1.5\times$ and $2.0\times$ traffic results this is not the case, as the traffic growth simulated is greater.

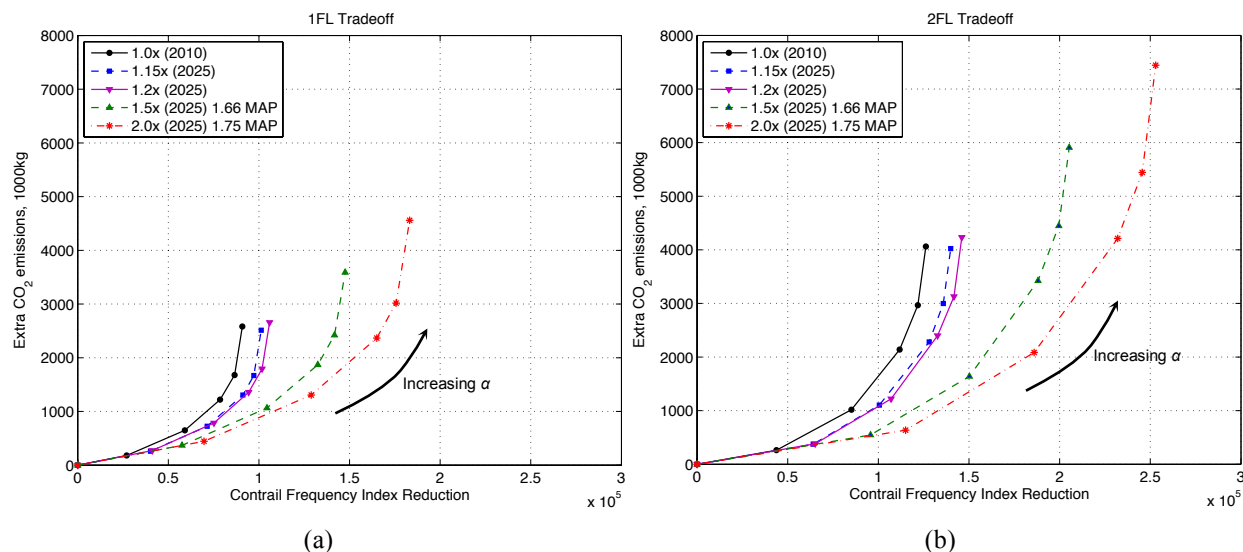


Figure 5. Trade-off between Contrails and CO₂: a) allowing shift of 1 flight level (2,000ft), and b) allowing shift of 2 flight levels (4,000ft). For each line, results are plotted for α values of 0, 20, 40, 80 and ∞ , from left to right.

It is also noted that both the reductions in CFI and increases in CO₂ emissions are significantly larger when aircraft are allowed to shift by two flight levels (in Figure 5b) as opposed to only one (in Figure 5a), as expected. Of note, however, is that for any given level of CO₂ emissions, the corresponding CFI is higher when aircraft are allowed to shift by two flight levels (in Figure 5b) than when they are allowed to shift by only one level (in Figure 5a). For example, if extra CO₂ emissions are limited to 2,000 tonnes, with a shift in two flight levels the maximum CFI reduction under 2.0 \times 2025 traffic would be just over 180,000 minutes. With a shift in only one flight level, the maximum CFI reduction would be just over 150,000 minutes. This suggests that allowing shifts by more flight levels is likely to result in greater CFI reduction, for given levels of extra CO₂ emissions.

The results presented in Figure 5 were also generated for an unconstrained scenario, in which sector capacities were not applied. This resulted in greater CFI reduction, as well as increased CO₂ emissions than shown in Figure 5, as more flights were permitted to shift flight levels in order to avoid contrail formation. The differences in CFI reduction and extra CO₂ emissions were relatively small, however – around 5% – indicating that sector constraints, assuming capacity was increased in the 1.5 \times and 2.0 \times traffic cases, would not limit the potential for reducing contrail formation significantly.

C. Trade-off between AGTP and Fuel Use

Figure 6 shows the trade-off between change in AGTP and extra fuel use, for different values of α . The change in AGTP results from both the reduction in contrails formation and the extra CO₂ emissions. Extra fuel use, which is directly proportional to extra CO₂ emissions, provides an indication of cost to flight operators, as fuel is the single largest flight operating cost incurred by flight operators. Total AGTP and total fuel burn were not plotted in this figure because both differ significantly between traffic forecasts, especially in comparison to the relatively small changes in AGTP and fuel use for different values of α . Total AGTP is plotted in Figure 7 for comparison. As in Figure 5, results are plotted for α values of 0, 20, 40, 80 and ∞ , from left to right.

Figure 6a shows results allowing aircraft to be shifted by only one flight level (2,000ft), while Figure 6b shows results allowing aircraft to be shifted by up to two flight levels (4,000ft). In both plots in Figure 6, the time horizon specified for the calculation of AGTP is 50 years, while the efficacy is 0.8. The results are presented using alternate values in Section IV-B. In both Figure 6a and Figure 6b, and at all forecast traffic levels, AGTP initially decreases with increasing fuel use (and increasing α), before leveling off and beginning to increase again past an α value of approximately 80. This is consistent with the results presented in Ref. 45 – the decrease in AGTP due to the reduction in contrails initially outweighs the increase in AGTP due to the extra CO₂ emissions. However, as greater deviation is required to reduce contrails further, the increase in AGTP due to the extra CO₂ emissions begins instead to outweigh the decrease in AGTP due to any further reduction in contrails. The decrease in AGTP and the increase in fuel use are significantly greater in all cases when aircraft are allowed to shift by two flight levels (in Figure 6b) as opposed to only one (in Figure 6a), which is consistent with Figure 5 (extra CO₂ emissions are directly

proportional to extra fuel). It is noted, however, that the value of extra fuel at which minimum AGTP is achieved varies significantly across the different forecasts. Shifting only one flight level, the minimum AGTP is achieved at 550 tonnes of extra fuel under 1.15 \times traffic, whereas it is achieved at 950 tonnes of extra fuel under 2.0 \times traffic. Shifting two flight levels, the minimum AGTP is achieved at 950 tonnes of extra fuel under 1.15 \times traffic, and at 1,700 tonnes of extra fuel under 2.0 \times traffic. In contrast, the value of α at which the minimum AGTP occurs does not vary significantly, occurring at approximately $\alpha=80$ in all cases.

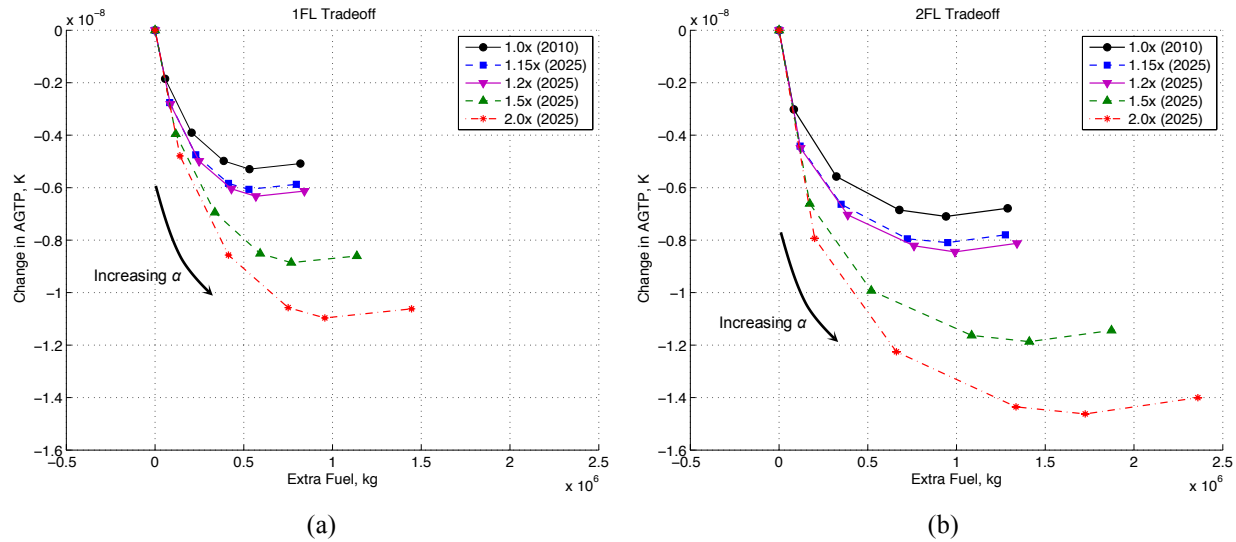


Figure 6. Trade-off between change in AGTP and extra fuel use relative to no contrail avoidance: a) allowing shift of 1 flight level (2,000ft), and b) allowing shift of 2 flight levels (4,000ft). For each line, results are plotted for α values of 0, 20, 40, 80 and ∞ , from left to right.

Figure 7 shows the same results as Figure 6, but with absolute AGTP plotted against extra fuel use. These plots provide an indication of how AGTP is impacted by the different forecast traffic levels. It is noted that the reduction in AGTP due to contrail avoidance is small in comparison to the difference in AGTP between the different traffic scenarios. Clearly, 2.0 \times traffic would be expected to have a greater impact on global average temperature than 1.15 \times traffic.

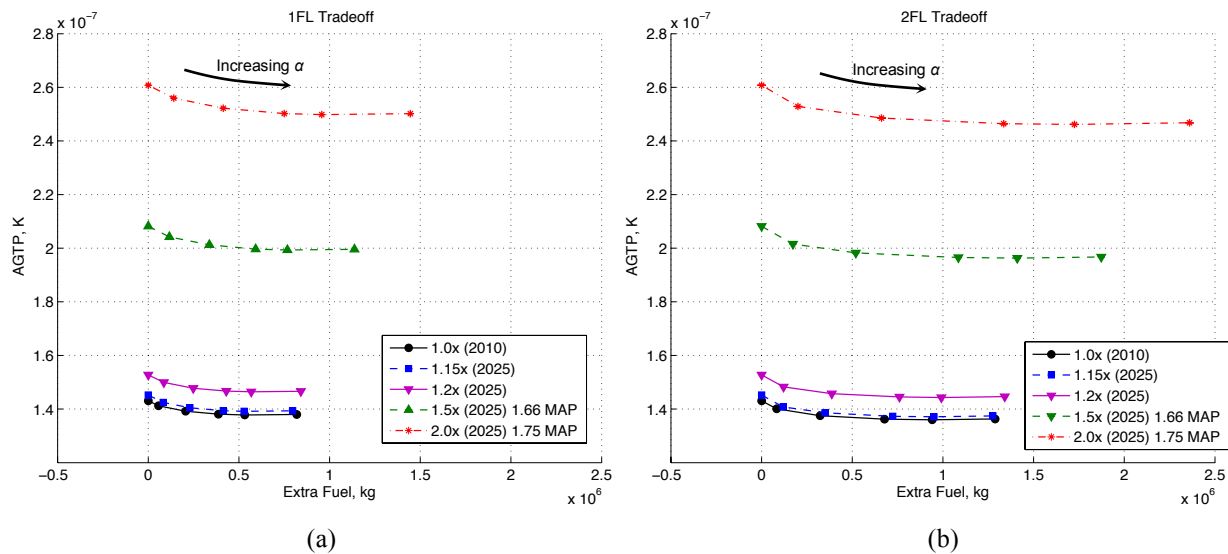


Figure 7. Trade-off between AGTP and extra fuel over no contrail avoidance: a) allowing shift of 1 flight level (2,000ft), and b) allowing shift of 2 flight levels (4,000ft). For each line, results are plotted for α values of 0, 20, 40, 80 and ∞ , from left to right.

IV. Sensitivity Analysis

The sensitivity of the results presented in Section III-B and -C are presented in the following section, including:

- The sensitivity of the trade-offs between contrail reduction and CO₂ emissions, and between change in AGTP and fuel use, to different weather days.
- The sensitivity of the trade-off between change in AGTP and fuel use to input parameters in the calculation of AGTP, particularly time horizon and efficacy.

A. Sensitivity of Results to Weather Days

Figure 8 shows the trade-off between contrail reduction and extra CO₂ emissions, shifting traffic by one and two flight levels (Figure 8a and Figure 8b respectively), under three different weather days in 2010: November 9, April 4 and March 24. Results are shown for these days because they are representative of days with low, medium and high levels of contrails across the NAS, respectively, and because there was low convective weather activity across the NAS in all cases. Convective weather activity may require significant rerouting, which would limit the maneuvers possible to avoid contrails as described in this paper. In all cases, 2.0× traffic is simulated. In both flight level cases (shifting traffic by one and two flight levels), there is a wide range of contrail reduction, and a corresponding wide range of extra CO₂ emissions. The shape of the trade-off between contrail reduction and extra CO₂ emissions remains the same, however, with diminishing returns as α increases. For any given limit on extra CO₂ emissions allowable, e.g. 2,000 tonnes, different days see very different contrail reduction, as would be expected.

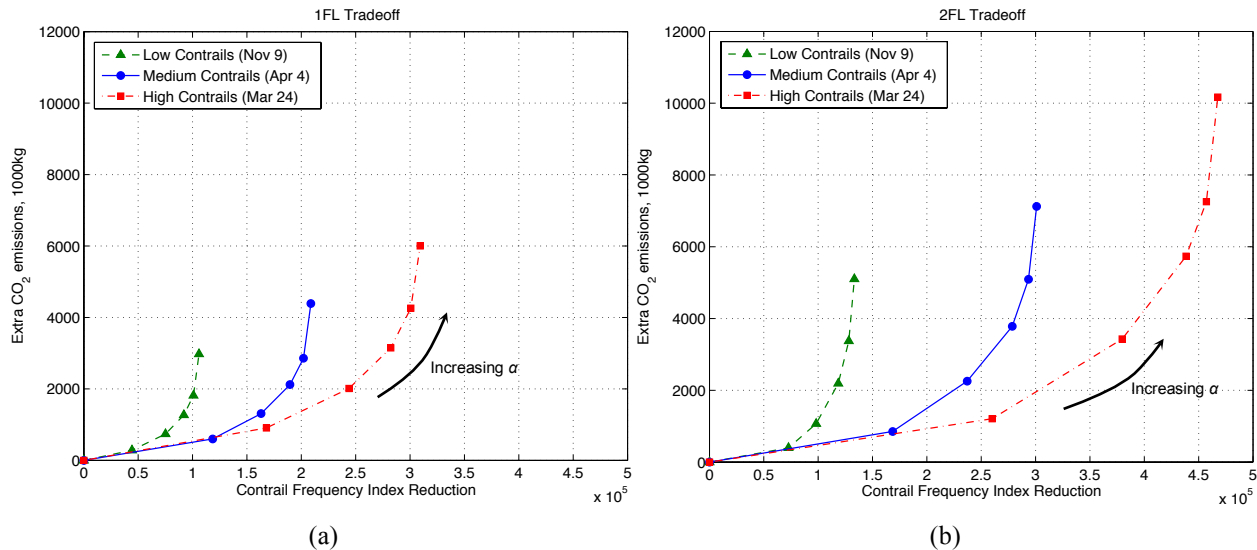


Figure 8. Trade-off between Contrails and CO₂ for different weather days, high traffic forecast (2.0× 2010 traffic): a) allowing shift of 1 flight level (2,000ft), and b) allowing shift of 2 flight levels (4,000ft). For each line, results are plotted for α values of 0, 20, 40, 80 and ∞ , from left to right.

Figure 9 shows the trade-off between change in absolute AGTP and total fuel use – a proxy for cost – shifting traffic by one and two flight levels (Figure 9a and Figure 9b respectively), under the same three weather days as Figure 8. Total AGTP and fuel use are shown, as opposed to changes in AGTP and extra fuel (which are shown in Figure 6), providing an indication of total impact and total cost. Consistent with Figure 8, there is a wide variation in change in AGTP and fuel use across the three days, but the shape of the trade-offs remain the same. In all cases, the minimum AGTP occurs at around $\alpha=80$, as in the results presented in Section III-C. This means that the level of fuel use at which AGTP is minimized increases with increasing contrails.

Both AGTP and fuel use shown in Figure 9 are in the order of 1,000× greater than the results shown in Ref. 45, which is consistent with the differences in number of flights simulated. We simulate traffic in the entire NAS, while Ref. 45 simulates traffic between 12 city pairs.

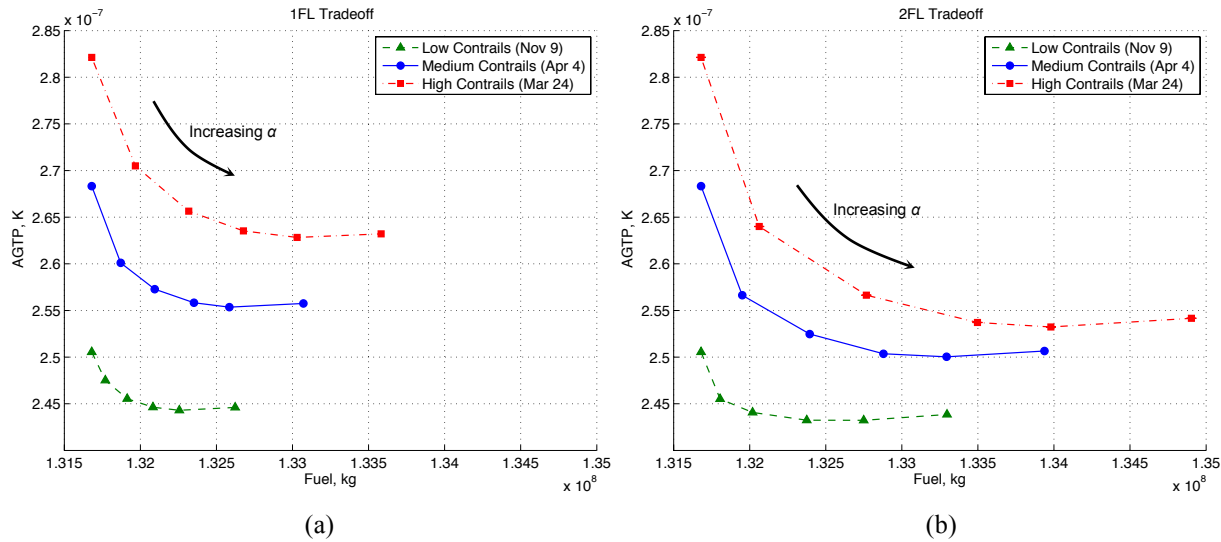


Figure 9. Trade-off between AGTP and fuel use for different weather days, high traffic forecast (2.0×2010 traffic): a) allowing shift of 1 flight level (2,000ft), and b) allowing shift of 2 flight levels (4,000ft). For each line, results are plotted for α values of 0, 20, 40, 80 and ∞ , from left to right.

B. Sensitivity of AGTP Results to Time Horizon and Efficacy

Figure 10 shows the trade-off between total AGTP and total fuel use, shifting traffic by one and two flight levels (Figure 10a and Figure 10b respectively), under different assumptions regarding quantifying the climate impact of contrails. Again, in all cases $2.0\times$ traffic is simulated. Results for three different time horizon's H are shown: 25 years, 50 years and 100 years. Error bars illustrate the range of results under different efficacy values, which are defined as the ratio of global temperature increase for a local energy input to that for a CO_2 -equivalent globally distributed energy input. Efficacy is varied from 0.6 (upper limit of error bar) to 1.0 (lower limit of error bar).

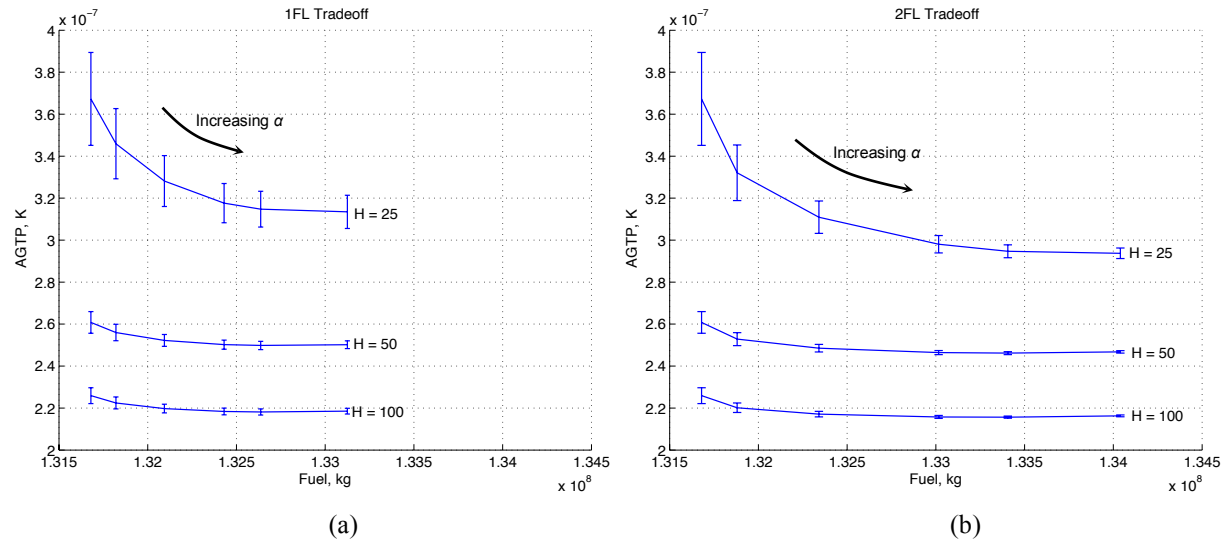


Figure 10. Trade-off between change in AGTP and extra CO_2 emissions, high traffic forecast (2.0×2010 traffic): a) allowing shift of 1 flight level (2,000ft), and b) allowing shift of 2 flight levels (4,000ft). Error bars show results with efficacy varying from 0.6 (upper limit of error bar) to 1.0 (lower limit of error bar). For each line, results are plotted for α values of 0, 20, 40, 80 and ∞ , from left to right.

The decrease in AGTP is significantly greater with a time horizon of 25 years than for either 50 or 100 years. This is expected as contrails have a temporary impact on the climate, so the impact of a pulse of contrails formed today on the future global average temperature decreases as we look further ahead in time. The environmental benefit of the avoided contrails remains the same in all cases, however, since it is short term and not impacted by time horizon.

Because of the reduced environmental cost of the extra CO₂ emissions with $H=25$ years, which works in opposition to the environmental benefit of reducing contrails, the minimum AGTP occurs with $\alpha=\infty$ (i.e., maximum contrail avoidance). This is not the case with $H=50$ or 100 years, where the minimum AGTP occurs at $\alpha=80$ (less than the maximum contrail avoidance). The two results for $H=50$ and 100 years are very similar, partly because pulse AGTP is plotted. If sustained AGTP were plotted there would be greater differences. In all cases, the gain in AGTP is small after total fuel use of about 1.33×10^8 kg, indicating that the results are fairly robust to different assumptions about the climate impact of contrails and CO₂ emissions.

V. Conclusions

The results presented in this paper suggest that contrail avoidance in the NAS by changing flight level is likely to have climate benefits under future traffic levels, particularly when aircraft can change altitude by up to two flight levels. The reduction in average global temperature rise by avoiding contrails is larger for higher forecasts of future traffic (e.g., the 2× traffic forecast), although the baseline average global temperature rise under these higher forecasts is significantly larger. The results also suggest that there are diminishing returns associated with changing flight level to avoid contrails, both directly in terms of contrail formation, and to an even greater extent in terms of climate impact, because of the climate cost of the increased CO₂ emissions associated with changing flight level. The results presented in this paper also suggest that the climate benefit from avoiding contrails is not significantly reduced by airspace capacity constraints, assuming that under the higher forecasts of traffic growth, airspace capacity would increase sufficiently to accommodate it. Also, while different weather days and different assumptions about the climate impact of contrails lead to significant changes in the results, the general trends remain unchanged, and the ratio of contrail impact to CO₂ impact at which climate impact is minimized remains approximately constant.

Future work in this area is also planned. As described earlier, this paper does not explicitly account for the fact that contrails only have a negative environmental impact during the night. It is assumed that all contrails remain long enough to have a negative impact during the following night. Research is planned to address this question in greater detail, and is likely to indicate that the climate impact of contrails in the NAS is less severe than predicted here, because some of the contrails modeled in this paper would not extend into the night. Fewer flight level changes would then be required, reducing the number of instances in which sector capacity constraints limit contrail reduction strategies. The research in this paper also doesn't account for the change in ozone formation at different altitudes due to aircraft NO_x emissions. While aircraft NO_x emissions do not change significantly with altitude, the impact of NO_x on ozone formation does. By flying at lower altitudes, less ozone is formed, reducing the average global temperature rise due to aviation. The impact of this effect for the altitude changes simulated in this research is not thought to be large, but this should be confirmed through further research. Finally, the research presented in this paper also does not prioritize which flight should be shifted based on its fuel burn. If only a limited number of flights can be shifted, because of sector constraints, the greatest environmental benefit would come from shifting those aircraft with lowest fuel burn. In the research presented in this paper, aircraft are shifted on a first-come-first-served basis only. Simulation of a more advanced strategy is left for future research.

References

- ¹ United Nations Intergovernmental Panel on Climate Change, "IPCC Special Report – Aviation and the Global Atmosphere, Working Group I and III," *IPCC*, Geneva, Switzerland, 1999.
- ² International Civil Aviation Organisation, "World Total Traffic 1995 – 2006," *ICAO*, Montreal, Canada, 2006.
- ³ Airbus, "Global Market Forecast 2011-2030," URL: <http://www.airbus.com/company/market/forecast/> [cited 21 December 2011].
- ⁴ Boeing, "Current Market Outlook 201-2030", URL: <http://www.boeing.com/commercial/cmo/> [cited 21 December 2011].
- ⁵ Berghof, R., A. Schmitt, C. Eyers, K. Haag, J. Middel, M. Hepting, A. Grübler, R. Hancox, "CONSAVE 2050 – Executive Summary, Competitive and Sustainable Growth," Competitive and Sustainable Growth, G4MA-CT-2002-04013, 2005, URL: <http://www.dlr.de/consave/CONSAVE%202050%20Executive%20Summary.pdf> [cited 21 December, 2011]
- ⁶ Schäfer A., "Long-Term Trends in Global Passenger Mobility," *The Bridge*, The National Academies Press, Washington, D.C., 2006, Vol. 36, pp. 24-32.
- ⁷ Cairns S., C. Newson, B. Boardman, J. Anable, "Predict and Decide – Aviation, Climate Change and UK Policy, Final report," Environmental Change Institute, University of Oxford, Oxford, UK, 2006.

- ⁸ Waitz, I., Townsend, J., Cutcher-Gershenfeld, J., Greitzer, E., and Kerrebrock, J., "Report to the United States Congress: Aviation and the Environment, A National Vision, Framework for Goals and Recommended Actions," Tech. rep., Partnership for AiR Transportation Noise and Emissions Reduction, London, UK, December 2004.
- ⁹ European Union. Directive 2008/101/EC of the European Parliament. Official Journal of the European Union, January 13, 2009, pp. 3-21.
- ¹⁰ PARTNER (Partnership for AiR Transportation Noise & Emissions reduction), 2009. "Project 31: Economic and Environmental Effects of the Introduction of a Cap-And-Trade Policy in Aviation," Massachusetts Institute of Technology, 2009, URL: <http://web.mit.edu/aeroastro/partner/projects/project31.html> [cited 2 November, 2009].
- ¹¹ Gierens, K., Limb, L., and Eleftheratos, K., "A Review of Various Strategies for Contrail Avoidance," *The Open Atmospheric Science Journal*, Vol. 2, 2008, pp. 1-7.
- ¹² Noppel, F. and Singh, R., "Overview on Contrail and Cirrus Cloud Avoidance Technology," *Journal of Aircraft*, Vol. 44, No. 5, 2007, pp. 1721-1726.
- ¹³ Meerkotter, R., Schumann, U., Doelling, D. R., Minnis, P., Nakajima, T., and Tsushima, Y., "Radiative forcing by contrails," *Annales Geophysicae*, Vol. 17, 1999, pp. 1080-1094.
- ¹⁴ Mannstein, H., Spichtinger, P., and Gierens, K., "A note on how to avoid contrail cirrus," *Transportation Research, Part D, Transport and environment*, Vol. 10, No. 5, September 2005, pp. 421-426.
- ¹⁵ Fichter, C., Marquart, S., Sausen, R., and Lee, D. S., "The impact of cruise altitude on contrails and related radiative forcing," *Meteorologische Zeitschrift*, Vol. 14, No. 4, August 2005, pp. 563-572.
- ¹⁶ Williams, V., Noland, R. B., and Toumi, R., "Reducing the climate change impacts of aviation by restricting cruise altitudes," *Transportation Research, Part D, Transport and environment*, Vol. 7, No. 5, November 2002, pp. 451-464.
- ¹⁷ Williams, V. and Noland, R. B., "Variability of contrail formation conditions and the implications for policies to reduce the climate impacts of aviation," *Transportation Research, Part D, Transport and environment*, Vol. 10, No. 4, July 2005, pp. 269-280.
- ¹⁸ Campbell, S. E., Neogi, N. A., and Bragg, M. B., "An Optimal Strategy for Persistent Contrail Avoidance," *AIAA Guidance, Navigation and Control Conference*, AIAA-2008-6515, AIAA, Honolulu, HI, August 2008.
- ¹⁹ Chen, N.Y., Sridhar, B., and Ng, H.K., "Trade-off between Contrail Reduction and Emissions in United States National Airspace", *Journal of Aircraft*, 2012 [Accepted for publication].
- ²⁰ Sridhar, B., H.K. Ng, N.Y. Chen, 2012. "Integration of Linear Dynamic Emission and Climate Models with Air Traffic Simulations," *AIAA Guidance, Navigation, and Control Conference*, Minneapolis, MN, 13 - 16 August 2012.
- ²¹ JPDO, "Next Generation Air Transportation System (NGATS) Integrated Plan," 2004, URL: www.jpdo.gov/library/ngats_v1_1204r.pdf [cited 27 December 2011].
- ²² FAA, "FAA Aerospace Forecast 2011-2031," URL: http://www.faa.gov/about/office_org/headquarters_offices/apl/aviation_forecasts/aerospace_forecasts/2011-2031/ [cited 27 December 2011].
- ²³ FAA, "Terminal Area Forecast 2009-2030", 2009, URL: <http://aspm.faa.gov/main/taf.asp> [cited 27 December 2011].
- ²⁴ Thompson, T., B. Miller, J. DiFelici, M. Brand, M. Zavareh, S. Augustine, J. Eckhouse, S. Hasan, J. Hees, D. Long, V. Stouffer, W. Crossley, R. Foley, "System-level Environmental Assessment of Concepts and Technologies (SEACAT)," Phase 1 Draft Final Report, Metron Aviation, LMI, Purdue Aeronautics & Astronautics, Dulles VA, 2011.
- ²⁵ Evans, A.D., Schäfer, A.S., "The Impact of Airport Capacity Constraints on Future Growth in the United States Air Transportation System," *Journal of Air Transportation Management*, 17, 2011, pp. 288-295.
- ²⁶ Crossley, W., R. Foley, "Initial Assessment of Demand Sensitivity and Fleet Composition to Fuel Price and General Economic Factors," Chapter IX, System-level Environmental Assessment of Concepts and Technologies (SEACAT), Phase 1 Draft Final Report, Metron Aviation, LMI, Purdue Aeronautics & Astronautics, Dulles VA, 2011.
- ²⁷ Huang, A.S., and D.R. Schleicher, "Futuristic US Flight Demand Generation Approach Incorporating Fleet Mix Assumptions," *AIAA Modeling and Simulation Technologies Conference and Exhibit*, 18-21 August 2008, Honolulu, Hawaii.
- ²⁸ NASA, "N+2 Advanced Vehicle Concepts NRA Draft Solicitation Synopsis," National Aeronautics and Space Administration, 2010, URL http://www.aeronautics.nasa.gov/calendar/era_preconference_synopsis.htm [cited 27 December 2011].

- ²⁹ Murphy, C., Ermatinger, C., Thompson, T., Augustine, S., White, T., Chan, J., Miller, B., and Zavareh, M., "Methods for Estimating Environmental Effects and Constraints on NextGen—2010 Portfolio Analysis Final Report." June, 2010.
- ³⁰ Becker, K., Nam, T., Kirby, M., and Mavris, D., "A Process for Future Aviation Environmental Impacts: A Surrogate Fleet Analysis Approach for NextGen," *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, Hilton Head, South Carolina, 21-23 September 2009.
- ³¹ Kirby M.R., and Mavris, D.N., "The Environmental Design Space." *26th International Congress of the Aeronautical Sciences*, Anchorage, AK, 14 - 19 Sep 2008.
- ³² Ponater, M., Marquart, S., and Sausen, R., "Contrails in a Comprehensive Global Climate Model: Parameterization and Radiative Forcing Results," *Journal of Geophysical Research*, Vol. 107, No. D13, 2002, pp. ACL 2–1.
- ³³ Duda, D. P., Minnis, P., Costulis, P. K., and Palikonda, R., "CONUS Contrail Frequency Estimated from RUC and Flight Track Data," *European Conference on Aviation, Atmosphere, and Climate*, Friedrichshafen at Lake Constance, Germany, June-July 2003.
- ³⁴ Gierens, K. M., Schumann, U., Smit, H. G. J., Helten, M., and Zangl, G., "Determination of humidity and temperature fluctuations based on MOZAIC data and parametrisation of persistent contrail coverage for general circulation models," *Annales Geophysicae*, Vol. 15, 1997, pp. 1057–1066.
- ³⁵ EUROCONTROL Validation Infrastructure Centre of Expertise, France, *User manual for the base of aircraft data (BADA)*, 3rd ed., March 2009.
- ³⁶ O'Neill, M., J. Dumont, T. Reynolds, J., Hansman, "Methods for Evaluating Environmental and Performance Trade-offs for Air Transportation Systems," *11th AIAA Aviation Technology, Integration and Operations Conference (ATIO)*, Virginia Beach, VA, September 2011.
- ³⁷ Fuglestedt, J., Shineb, K., Berntsen, T., Cook, J., Lee, D., Stenke, A., Skeie, R., Velders, G., and Waitz, I., "Transport impacts on atmosphere and climate: Metrics," *Atmospheric Environment*, Vol. 44, No. 37, December 2010, pp. 4648-4677.
- ³⁸ Sausen, R., and Schumann, U. "Estimate of the climate response of CO₂ and NO_x emissions scenarios," *Climate Change*, 44, pp 27-58, 2000.
- ³⁹ Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Van Dorland, R., 2007a. Changes in atmospheric constituents and in radiative forcing. In: Solomon, S., et al. (Eds.), *Climate Change 2007: the Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
- ⁴⁰ Meerkötter, R., Schumann, U., Minnis, P., Doelling, D. R., Nakajima, T., and Tsushima, Y. "Radiative Forcing by Contrails," *Ann. Geophysicae*, Vol. 17, 1999, pp. 1080-1094, doi: 10.1007/s00585-999-1080-7.
- ⁴¹ Ponater, M. "Distinctive Efficacies of the components contributing to total aviation climate impact," *Proceedings of the 2nd International Conference on Transport, Atmosphere and Climate (TAC-2)*. 22-25 June 2009, DLR-Forschungsbericht 2010-10, Kö ln-Porz, Germany, ISSN 1434-8454. Aachen, Germany, and Maastricht, The Netherlands, 2009, pp. 227- 232.
- ⁴² NASA, "Airspace Systems Program, Next Generation Air Transportation System Concepts and Technology Development, FY2010 Project Plan Version 3.0," National Aeronautics and Space Administration, May 18, 2010, URL: http://www.aeronautics.nasa.gov/pdf/ctd_project_plan_2010_508.pdf [cited 27 December 2011].
- ⁴³ Zelinski, S. and C.F. Lai, "Comparing Airspace Design Methods" *Airspace Systems Program Technical Interchange Meeting*; San Diego, CA, March 2011.
- ⁴⁴ Erzberger, H., "Automated Conflict Resolution for Air Traffic Control" *25th International Congress of the Aeronautical Sciences*; Hamburg, Germany, September 2006.
- ⁴⁵ Sridhar, B., H.K. Ng, N.Y. Chen, 2012. "Uncertainty Quantification in the Development of Aviation Operations to Reduce Aviation Emissions and Contrails," *28th International Congress of the Aeronautical Sciences*, Brisbane, Australia, 23-28 September 2012.